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MAGNETOCONVECTION ON THE SOLAR SURFACE

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Abstract. We describe and illustrate the first high-resolution observations of horizontal flows on the solar surface and their relation to magnetic field structure seen in the Sun's photosphere. The velocity data were deduced from white-light images obtained by the Solar Optical Universal Polarimeter (SOUP) instrument flown as part of NASA's Spacelab 2 mission (Space Shuttle flight 51-F, STS-19). Solar granules (with a typical size scale of 1 Mm and lifetime of 15 min) were used as tracers to measure larger-scale, longer-lived flows including mesogranules (6-12 Mm), supergranules (30 Mm), radial outflows from a sunspot, and streams (of length 50-100 Mm, width 5-10 Mm). These flows were compared to a 9-hour time series of the solar magnetic field obtained at the same time at the Big Bear Solar Observatory (BBSO). The flow field and the magnetic structure agree in remarkable detail. Indeed, the data suggest strongly that the flow field is a nearly perfect descriptor of the motion and evolution of the magnetic field (with the exception of the strongest fields within active regions which are able to inhibit the convection). If such measurements can be made synoptically from space, or under good seeing conditions from a ground-based observatory, it should be possible to pinpoint loci of magnetic mixing, twisting, and stress buildup, and thus predict the occurrence of solar flares, coronal heating, and mass ejections.

Introduction

More than a quarter century ago, Leighton et al. (1962) discovered the solar supergranulation flow field. Shortly thereafter Simon and Leighton (1964) suggested that the supergranulation carries the solar magnetic field to the flow cell boundaries to form the well-known chromospheric network pattern long seen in calcium, hydrogen, and magnetic images.

Developments in magnetoconvection theory (Weiss, 1978; Meyer et al., 1979; Galloway and Weiss, 1981; Parker, 1982) showed how the motion of supergranules could redistribute and concentrate magnetic flux tubes in and below the solar surface. Recent works have extended the earlier studies to include motions in granules (Schmidt et al., 1985), and applied more elaborate two-dimensional and three-dimensional computational techniques (Proctor and Weiss, 1982; Galloway and Proctor, 1983; Nordlund, 1985a,b; Cattaneo, 1984; Hurlburt and Toomre, 1988). The theoretical analyses suggest that the observed magnetic and intensity structures in the surface and higher layers of the solar atmosphere depend on the nature of both large-scale (supergranular, mesogranular) and small-scale (granular) sub-surface flows.

Several observers (Simon, 1967; Muller and Mena, 1987; Title et al., 1987) have attempted to relate the motions of granules to magnetic structures, and many others (Vrabec, 1971; Smithson, 1973; Schroter and Wöhl, 1975; Mosher, 1977; Martin, 1988; Title et al., 1987) have measured the motions of individual magnetic field elements relative to the magnetic network.

Taken together, these observations imply that both the large-scale supergranular flow and the much smaller motion fields of individual granules help to determine the structure of magnetic field

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on the Sun's surface. Both the observations and theory suggest that the flow determines the evolution and distribution of the magnetic fields. However, in active regions where the field is strong, it is clear (Zwaan, 1978) that the magnetic field has a significant effect on the flow field.

The work described above provides the background and sets the stage for the remarkable observations from Spacelab 2 which we now describe in the following sections.

Data

The white-light data were obtained on 35 mm film by the Solar Optical Universal Polarimeter (SOUP) instrument flown on Spacelab 2 (NASA Space Shuttle mission 51-F). SOUP contained a 30-cm Cassegrain telescope and an active secondary mirror for image stabilization (Title et al., 1986). In this paper we used images from orbit 110 taken between 19:10:35 UT and 19:38:05 UT on August 5, 1985, in the vicinity of active region 4682. Frames were obtained every 2 s. The field-of-view covered an area 166 by 250 arc sec. The effective wavelength band of the observations is roughly 1000 Å centered on 6000 Å. The magnetic data were obtained by the Big Bear Solar Observatory (BBSO) on the same active region from August 5, 1985, 15:25:43 UT to August 6, 00:50:54 UT.

The high-quality granulation pictures taken by SOUP provided a unique opportunity to detect large-scale surface flows by direct displacement measurements of the local intensity pattern. We have applied correlation tracking methods to make the required measurements (November et al., 1987; November and Simon, 1988). The flow field is detectable because it advects the granulation pattern. That is, granulation serves as a tracer for the flow. Since granules typically last 10 to 15 min, measurements must be made in a time short compared to this lifetime. In addition, because the 5-min oscillation is also present in the movies (Title et al., 1986), measurements must be separated by considerably less than 2.5 min. We have used time differences between images of 10 to 60 s in this study. This seems adequate since velocities obtained from images up to 60 s apart do not differ significantly. Because the supergranulation flow ranges from 0.1 to 1 km s^{-1}, in a 30-s interval the local granulation pattern should move typically about 10 km or 15 milliarc sec. Due to atmospheric turbulence ("seeing"), the best ground-based imagery is rarely better than about 1 arc sec, and it contains distortions of magnitude comparable to the blurring. Clearly, with typical noise-to-signal ratios of about 100, measuring with confidence such small displacements had previously been very difficult. Details of the data reduction have been discussed by Simon et al. (1988).

Analysis

Shown in Figure 1 are (a) a SOUP image, (b) a BBSO magnetogram at nearly the same time, (c) the SOUP flow field (shown as vectors) overlayed on a gray-scale map of the divergence of the flow field, and (d) the SOUP flow field superposed on the magnetogram. Velocities generally lie in the range 100 to 800 m s^{-1} and represent the average value obtained by correlation tracking over the 28-min observation time of orbit 110. The divergence of the horizontal flow vector is approximately proportional to the average vertical velocity (November et al., 1987) and thus identifies cell interiors (sources or upflows) and boundaries (sinks or downdrafts). The numbers in Figures 1c and 1d indicate the centers of four strong cellular outflows; note that these centers are void of magnetic flux.

We see from Figure 1 the intimate relation between the flow field and the magnetic field. In relatively compact magnetic features, the flow field points toward the concentrations. In cell-like regions of the magnetogram the vectors of the flow field point radially outward from the cell centers toward the boundaries (network). We also see a third type of magnetic structure where the flow field converges, not to a sink point, but to a line. In the active region, other large-scale flows occur. The first and most striking discovery in the SOUP data was an annulus, about 5 arc sec wide extending from the edge of the sunspot penumbra into the surrounding photosphere, composed of radially out-streaming granules (Title et al., 1986). This confirmed a long-held opinion; namely, that because of its strong magnetic field, the spot inhibits normal convection to the surface, so one might expect that upflows would be diverted radially outward from the sunspot (Meyer et al., 1974). We observe that magnetic field motions across this annulus closely follow the flow vectors determined from the pattern of granular motions. This is the well known moat flow in which magnetic features flow radially out from the sunspot (Sheeley, 1969, 1971; Sheeley and Bhatnagar, 1971; Vrabec, 1971). We also observe that the pore region acts as a large sink, especially for flows streaming outward from the sunspot.

Another remarkable new result is the existence of streams (or currents), particularly in quiet Sun regions. We had thought that the Sun is covered by closely packed cellular structures of several scales (granules, mesogranules, supergranules) with old cells disappearing as new ones are formed. However, we see in Figure 1 that there are also several streams, some of which are 50-100 Mm in length and 5-10 Mm in cross section, where there exist no large scale cellular structures. The most striking of these begins at the left boundary of Figure 1 and extends halfway across the bottom part of the image.

We gain additional insight into the relationship between flows and magnetic fields by asking

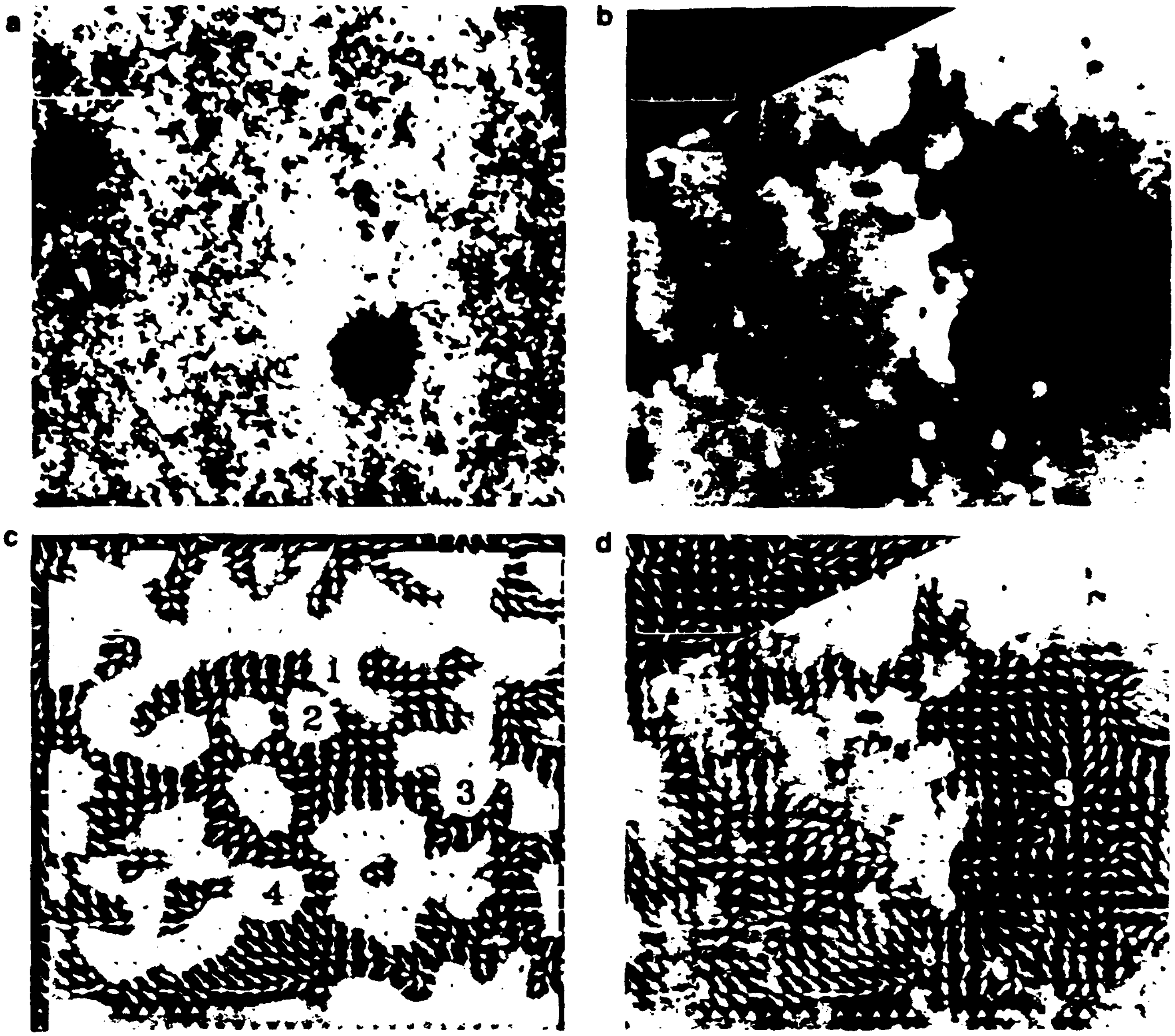

Fig 1. Comparison of SOUP and BBSO data obtained on August 5, 1985, at 19:28 UT. The field-of-view is 137 by 128 arc sec in the vicinity of active region 4682. A scale with 5 arc sec ticks is on each image. (a) SOUP white-light image, (b) BBSO magnetogram, (c) SOUP flow vectors superposed on a gray-scale image of the flow divergence (sources are bright, sinks dark), and (d) SOUP vectors superposed on the magnetogram. Four flow cells are identified in (c) and (d).

where the measured surface flow field would carry hypothetical free particles ("corks") originally distributed uniformly in the flow field. We calculated the cork flow by moving each cork according to the velocity of the local flow field at that cork's location. In Figure 2 we show the location of such corks overlaid on a magnetogram after 12 hours. The same four flow cells are marked, as in Figure 1. Most of the stable magnetic structures (i.e., those which show little or no motion during the nine hour movie) outside the sunspot are located at or near corks. And in places where we see magnetic flows, the movies show similar motions of corks and magnetic features. Initially the flow carries corks to the cell boundaries. Then the corks creep along the

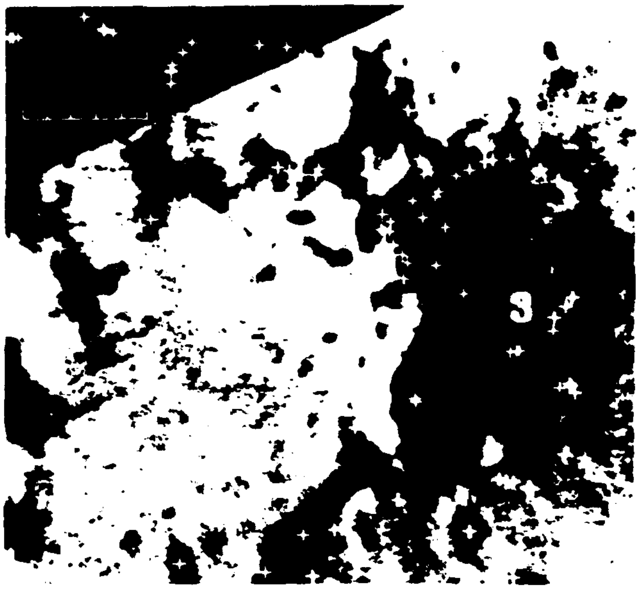

Fig 2. The same area as Figure 1, showing the positions of "corks" after 12 hours under the action of a constant flow field.

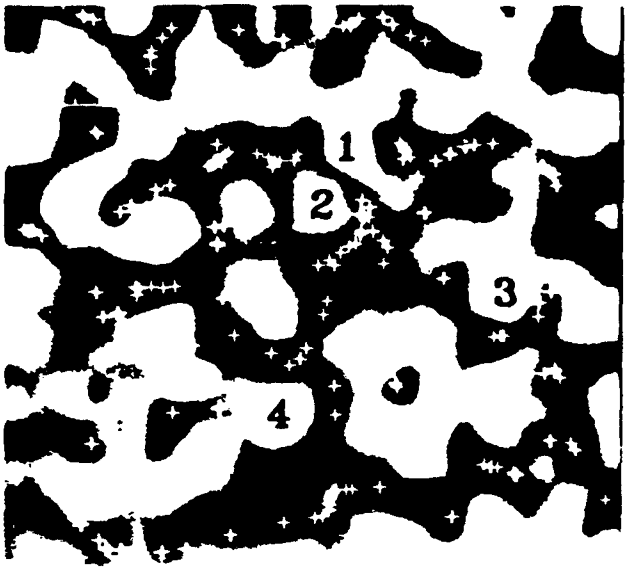

Fig 3. Divergence of the flow field of Figure 1 superposed on the corks after 12 hours. The cork pattern mainly shows a network of supergranular scale, in which mesogranules are embedded.

boundaries to sink regions which usually are vertices in the network pattern as seen in calcium, hydrogen, or magnetograms. We have made a magnetogram movie overlayed with the SOUP white-light flow field vectors, from which it is very clear that in the quiet Sun small magnetic field elements appear randomly near supergranule/ mesogranule centers, rapidly move to cell boundaries, and then flow slowly along the boundaries, just as the cork model suggests. The movie also contains several examples in which a ring of magnetic network surrounding a cell increases in diamter; this suggests that the flow cell is similarly increasing in diameter.

It is interesting to note, however, that the magnetic (or cork) network sometimes shows a larger dominant cell size than do the flow maps. This is illustrated in Figure 3, where we have superposed a divergence map of the flow in Figure 1 and a snapshot of the corks after 12 hours. It shows that two or three smaller cells of mesogranular scale (November et al., 1981) are often contained within one traditional network cell. Cell sizes (center-to-center) in the flow divergence maps are often 6 to 12 Mm rather than the 30 Mm value usually associated with supergranulation.

Discussion

These simultaneous observations of white-light granulation and digital magnetograms have shown clearly the intimate interactions between surface motions and magnetic structures. We are able to demonstrate that the white-light granular flow field is a nearly perfect descriptor of the motion and evolution of the magnetic field. The flow field determined from one 28-min measurement is an excellent indicator of the motion of the corresponding magnetic field configuration and is valid for at least 4 hours before and after the SOUP observations. From the cork simulations we estimate that the magnetic pattern would require about 8 to 10 hours to develop, which suggests that the flow field and magnetic field have a lifetime longer than 10 hours as would be expected for large-scale supergranular structures.

Especially in quiet Sun regions, both the magnetograms and the cork simulation show an incomplete network: fully outlined cells are rare, and usually there are just enough markers in the boundaries to suggest a cellular pattern. The cork simulation shows that this is an intrinsic property of the flow patterns and not only a result of insufficient magnetic flux to complete the pattern.

These data suggest to us that flow along network boundaries may be an important feature in the evolution of the magnetic field pattern. This has implications for understanding phenomena such as coronal heating and the buildup of magnetic stresses in the network. First, flow along the network boundaries will tend to mix and twist the fields on very small scales. We have measured the vertical component of vorticity of the flow field and find that at some locations it reaches values of about 0.0001 s^{-1}. Thus substantial twist can be imparted to the magnetic field in only a few hours where the vorticity is large. The mixing and twisting will also be enhanced by local displacements of the field caused by randomly-directed motions and explosions of individual granules. Second, flow along the boundaries concentrates fields in vertices. These vertices are probably stable points in the flow field, so that new supergranules may form with a vertex at the previous boundary.

Such observations are valuable to theorists who have argued that dissipation and heating in magnetic regions depend critically on the spatial scale of the twisting of the flux tubes (van Ballegooijen, 1986; Parker, 1972, 1983). For example, Mikic et al. (1988) have used three-dimensional models to show how shearing photospheric flows might build up the energy of a magnetic arcade until it becomes unstable, forms current sheets, and then reconnects with rapid release of magnetic energy in the corona.

Just as the Doppler spectroheliogram observations of Leighton et al. (1962) made the phenomenon of supergranulation clearly recognizable near the limb, local correlation tracking can make horizontal flow patterns apparent at disk center. This latter geometry is much better suited to search for giant cell patterns (Simon and Weiss, 1968), banana cells (Hart et al., 1986a,b), and circumferential rolls (Ribes et al., 1985; Wilson, 1987). With this new technique we have already obtained the first clear maps of the mesogranulation pattern discovered by November et al. (1981), and characterized its effect in magnetic field evolution.

It is unfortunate that we are unable to make further measurements from space of these phenomena at the present time, since no suitable spacecraft is in orbit, nor is any planned for the next 5 years. In the interim, we are developing techniques and instrumentation to obtain similar data from ground-based observations. While atmospheric turbulence will degrade the image quality and make data reduction more difficult, we believe that under reasonably good seeing conditions (1 to 2 arc sec) this powerful technique will still be viable and will permit us to make significant progress in observing and explaining the buildup and dissipation of magnetic energy at the solar surface. Such observations have been underway for the past year, and are already beginning to yield promising results.

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